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COMPOSITION

Prior to 1961 it was generally accepted that the main constituent of the atmosphere above 300 km was atomic oxygen up to an altitude of about 1000 km and that at higher altitudes hydrogen would predominate. Direct experimental evidence for the presence of neutral hydrogen in the outer atmosphere has come from the high resolution Lyman α spectrum obtained by Purcell and Tousey (1960). From the absorption core of their Lyman α spectrum, the total content of hydrogen above the altitude of the rocket measurement has been determined. Johnson (1961) has interpreted this hydrogen content to be distributed in the form of a "geocorona". The problem of interpretation of the Lyman α observations in terms of hydrogen and its location with respect to the earth has recently been reviewed in detail by Donahue (1962). The computation of the distribution of neutral hydrogen is complicated by the fact that at magnetospheric levels "exospheric" conditions prevail, i.e., the mean free path of neutral hydrogen is greater than the local scale height. Because of the escape of particles with high velocities, the velocity distribution is, strictly speaking, non-maxwellian and the distribution of density with height does not follow the simple hydrostatic equation, but has to be computed by taking into account ballistic escape, ballistic re-entry and bound-orbiting particles. Such computations have been made by Öpik and Singer (1961) and by Johnson (1961). Out to a geocentric distance of about two earth radii, a simple hydrostatic distribution, however, still represents a reasonably good approximation.

Photoionization and/or charge exchange with oxygen ions of the neutral hydrogen of the geocorona lead to the protons constituting the "protonosphere". The ions at magnetospheric levels are distributed according to a diffusive equilibrium distribution, i.e., hydrostatically supported but constrained by the earth's magnetic field. For ions the mean free path is short enough so that the concept of an ion-exosphere is not applicable (Johnson, 1962). While the diffusive equilibrium distribution of an ionic species was generally considered to be governed by a scale height twice that of the corresponding neutral species, it was pointed out by Mange (1960, 1961) that this concept is not justified for a minor ion in the presence of other ions. The electric field which is set up to prevent further charge separation of electrons and ions diffusing under gravity, and which is proportional to the mean mass of the (singly charged) positive ions, causes a minor light ion first to increase with altitude until it becomes predominant after which it will show the usual exponential decrease with altitude according to a scale height approaching twice that of the corresponding neutral constituent. Subsequently to Mange's independent derivation of the equation governing the distribution of singly charged ions in the presence of other singly-charged ions, it was realized that the same problem had been solved before by Dungey (1955), and originally as long as four decades ago (Pannekoek, 1922; Eddington, 1926). The distribution of protons in the protonosphere according to this concept and their relation and coupling to the ionospheric F-region where oxygen ions predominate, has been discussed in great detail by Hanson and Ortenburger (1961).

In 1961, Nicolet (1961) suggested that neutral and ionized helium should be an important constituent in the upper atmosphere. He pointed out that the presence of neutral helium would provide a sensible solution to the problem of high atmospheric densities at 1600 km deduced from the drag of the Echo I balloon satellite. The first experimental evidence from charged particle observations, for the importance of helium in the upper atmosphere was presented before a session of U. S. Commission 4 at the Fall-URSI-Meeting in Austin, Texas, 1961. (Hanson, 1962; Bourdeau, Whipple, Donley and Bauer, 1962.) Hanson (1962), inferred the presence of helium ions from an ion density profile obtained by Hale (1961) with a Scout rocket. Hanson concluded from the analysis of this data that the concentration of He^+ was in agreement with Nicolet's estimates and that the layer where He^+ was predominant extended over about 2000 km, from 1200 to 3400 km at a time when the atmospheric temperature corresponded to $1600^{o}K$. He also suggested that He^+ is lost by an ion-atom interchange process involving molecular nitrogen and that no large diurnal change in the helium ion concentration should occur. More recently Bates and Patterson, (1962), have shown that the loss process for He^+ with N_2 is not possible, but that the one involving O_2 seems to be responsible for the loss of He^+.

The first direct experimental evidence for the presence of He^+ was provided by the ion retarding potential measurement on Explorer VIII (Bourdeau, Whipple, Donley and Bauer, 1962). This measurement showed a ratio of $He^+/O^+ = 1.3 \pm 0.3$ at an altitude of 1630 km, where the simultaneously measured electron temperature was $1750 \pm 200^{o}K$. Additional evidence for a transition from O^+ to He^+, rather than directly to H^+ has come from a rocket measurement of the electron density distribution (Bauer and Jackson, 1962). The presence of He^+ and H^+ in the upper atmosphere has now also been identified directly with an RF ion spectrometer (Taylor, Brinton and Smith, 1962).

More recently ion composition measurements on the Ariel satellite have also shown the presence of He^+ as well as a significant diurnal variation of the altitude range where He^+ is the predominant ion (Willmore, Boyd and Bowen, 1962). These data, as well as a recent nighttime ion density profile obtained with a Scout rocket (Donley, 1963), indicate that at low atmospheric temperatures the layer where He^+ is predominant is only a few hundred km thick compared to a thickness of 2000 km at 1600°K determined by Hanson, with correspondingly lower altitudes of transitions from O^+ to He^+ and He^+ to H^+. Such a strong variation with temperature in the thickness of the helium ion layer is in accordance with a suggestion by Bauer (1963).

The possible presence of doubly charged oxygen ions (O^{++}) in the upper ionosphere has been suggested by Nakada and Singer (1962) on the basis of the abundance of O^+ and an adequate photoionization rate for their formation. In this connection they have investigated the distribution of multiply charged ions in an ion mixture, for which no analytical expression of the kind derived by Mange (1960) exists, and have shown by numerical integration that the concentration of O^{++} would also increase with altitude relative to O^+ and may, depending on loss rates, become an important ionic constituent. The presence of O^{++}, however, has not yet been verified experimentally.

TEMPERATURE

The kinetic gas temperature of the atmosphere at magnetospheric levels has been determined from satellite drag observations assuming model distributions of the mean molecular weight. Above 300 km this temperature should be independent of altitude because of the high thermal conductivity. The kinetic gas temperature in this isothermal region has been found to vary with the solar cycle and to show short-term fluctuations which are correlated with the 10.7 cm radiation from the sun, as well as with geomagnetic activity (Jacchia, 1961; Priester, 1961; Harris and Priester, 1962). A diurnal variation having a minimum at 4 a.m. local time and a maximum at about 2 p.m. is indicated from the satellite data.

While the kinetic gas temperature in the upper atmosphere has only been inferred from satellite drag measurements, direct measurements of the electron and ion temperatures have been made with the help of space vehicles. The vertical profiles of electron temperature up to about 400 km have been measured by means of the Langmuir probe technique (Spencer, Brace and Carignan, 1962; Brace, 1962). These measurements indicate that at mid-latitudes for quiet ionospheric conditions, the daytime electron temperature attains a maximum at about 230 km, approaching an isothermal behavior at altitudes above 300 km.

This measurement is in good agreement with theoretical investigations (Hanson and Johnson, 1961; Hanson, 1962; Dalgarno, McElroy and Moffett, 1962), which show that for solar ultraviolet as the major heat source, the only departure from temperature equilibrium would occur in the region between 200 and 400 km altitude. At higher altitudes, the daytime electron temperature and the ion (and gas) temperature is expected to be equal, at least under quiet conditions. A nighttime measurement of electron temperature shows perfect isothermal behavior throughout this altitude range (Brace, 1962). Departures from thermal equilibrium extending throughout the ionospheric F-region have been reported for disturbed ionospheric conditions at middle latitude and appear to be the rule in auroral regions (Spencer, Brace and Carignan, 1962). The gas temperature in the upper ionosphere has also been determined from the exponential decrement of electron and ion density profiles. These measurements show evidence of an isothermal behavior, since the scale height of the electron-ion gas is constant within a few percent over an altitude range of a few hundred km. Temperatures derived from these scale heights, assuming thermal equilibrium, have been found to be in good agreement with kinetic gas temperatures expected from the correlation with solar 10.7 cm flux, thus providing indirect evidence for temperature equilibrium (Bauer and Bourdeau, 1962). Direct measurements of electron temperature at magnetospheric levels have been made by means of Langmuir probes on the Explorer VIII satellite (Serbu, Bourdeau and Donley, 1961). These measurements also show, within their error-limits, agreement with model values of kinetic gas temperatures, except during the sunrise period when high electron temperatures seem to be prevalent. More recently, similar measurements have been made on the Ariel satellite (Willmore, Boyd and Bowen, 1962) in the altitude region between 400 and 1200 km which indicate a latitude dependence, with midday values of 1200°K at the equator and 1600°K at a latitude of 55°N. Preliminary topside sounder satellite results are in qualitative agreement with such a latitude dependence (Knecht and Van Zandt, 1963). The Ariel measurements also show high electron temperatures during the sunrise period while at other times the electron temperatures are equivalent to the simultaneously determined ion temperatures.

Ion temperatures and the departure from thermal equilibrium in the upper ionosphere have also been determined by ground-based magnetospheric sounders using the incoherent backscatter technique. Evans (1962) has reported measurements for a few days covering an altitude range up to 800 km, which show temperature equilibrium ($T_e = T_i$) during the night as expected, but a positive temperature gradient, and during the day departures from equilibrium in the entire region above 200 km. The latter can be interpreted either as a constant ratio T_e/T_i, with T_e and T_i showing a height gradient, or as a variable ratio T_e/T_i, with T_i = constant and an even stronger height-dependence of T_e. The time of maximum departure from equilibrium according to his data is at noon, reaching a value of $T_e/T_i = 1.6$. This is in disagreement with satellite measurements which show high electron temperatures only during the sunrise period, as well as with incoherent backscatter measurements by Bowles, Ochs and Green, (1962), who also found the times of departure from thermal equilibrium to be only during the sunrise period and during disturbed ionospheric conditions. The present discrepancies between space-flight measurements of charged particle temperatures and those determined by means of the incoherent backscatter technique obviously need to be resolved. It should be understood, however, that generalizations concerning the thermal properties of the upper atmosphere based as yet upon only a small number of observations may be premature.

SUMMARY

During the past three years the main contributions to our knowledge of the constitution of the atmosphere at magnetospheric levels have been the identification of helium as an important constituent and direct measurements of the thermal properties of this region as a function of altitude, latitude and time.

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